

TORQUE RIPPLE MINIMIZATION OF BLDC MOTOR BY USING HYSTERISIS CURRENT CONTROLLER

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ABSTRACT

This paper proposes a method of minimization of torque ripple in Brushless DC (BLDC) motor with ideal back EMF under MATLAB 7.1/Simulink environment. An idealized BLDC motor has trapezoidal back EMF waveform. However, for practical reasons like non-uniformity of magnetic material and design parameters it is difficult to produce exact trapezoidal wave shape. Therefore torque ripple appears in conventional control. This paper, introduces the Hysteresis Current Control (HCC) method to minimize the torque ripple at commutation period. Hysteresis controller averages the incoming and outgoing phase current to minimize the dips and spikes in un-commutated phase current. This leads to minimize the torque ripple. Simulation results shows the apparent reduction in torque ripple when compared with conventional control.

KEYWORDS: Brushless DC Motor (BLDC), Torque Ripple, Commutation, Hysteresis Current Control

INTRODUCTION

Permanent magnet brushless DC (BLDC) motors most widely used in numerous applications, such as servo drives, computer peripheral equipments and electric vehicles due to their high power density, better speed versus torque characteristics, high dynamic responses, high efficiency, high speed ranges, long life, noise less operation and easier control. Trapezoidal back electromotive force (EMF) waveform characterizes an ideal brushless dc motor. It can be shown that for this back EMF, when the motor is fed by a rectangular phase current of 120° conduction mode zero torque ripple is produced (Miller, 1989). However for practical reasons, the parameters such as non-uniformity of magnetic material, inverter and motor design makes it difficult to produce the exact trapezoidal back EMF waveform (Carlson, 1992).

For achieving the rectangular current waveform, VSI (voltage source inverter) is used rather than CSI (current source inverter), because the only device with reverse blocking capability can be used for minimizing the current ripple and large inductor is required. But when VSI is used, the current ripple is produced by the phase current commutation. Torque ripple is produced due to current ripple during commutation period. Since, the motor windings are inductive, the current controller cannot produce the required di/dt in the commutation period, even in finite dc bus supply voltage. Therefore, torque ripple appears such that rectangular current is fed in conventional control.

Consequently, acoustic noise and vibrations in the high precision machines are caused due to speed oscillations, resonance in mechanical portions of the drive, by the undesired torque ripple in BLDC motor drives. Therefore, the main research works are focused on commutation torque ripple and the torque ripple reduction and the control performance improvement of BLDC have been the research hotspot in recent years.

The torque ripple in BLDC can be minimized either by the improving control scheme or by improving motor design. Improved motor control scheme include adaptive control technique, pre-programmed current waveform control, selective harmonic injection technique, estimators and observers, speed loop disturbance rejection, high speed current regulators, commutation torque minimizations and automated self commissioning schemes. On the other hand, skewing the slots, fractional slot winding, short-pitch winding, increased number of phases, air gap windings, adjusting stator slot opening and wedges, design in rotor magnet pole arc, its position and width characterize the improved motor designs.

Recently, in order to reduce current ripple numerous current controls have been proposed. The typical methods are PWM current control and hysteretic current control (Dixon, et al, 2002). First of all, the former has varying switching frequency, fastest speed of response, adjustable current ripple and filter size depends on Δi . In contrast, the later has fixed switching frequency, fast speed of response, fixed ripple current, filter size is usually small and less switching loss.

This paper presents a comprehensive analysis of the commutation torque ripple and HCC method in brushless dc motor drives. Note that the cogging torque and slot effect are not considered in this work. To enhance the current control performance, a hysteresis current controller is employed. During the commutation interval, balancing the slopes of incoming and outgoing phase currents is done by the proposed control scheme. The triggering pulse used to operate the inverter is calculated in the hysteresis current controller during commutation period.

This method operates optimal performance over the entire speed range despite being simple. Simulation results proved the effectiveness of proposed method.

OPERATION OF THE BLDC

Modelling of BLDC Motor

The block diagram of BLDC motor drive is shown in figure 1.

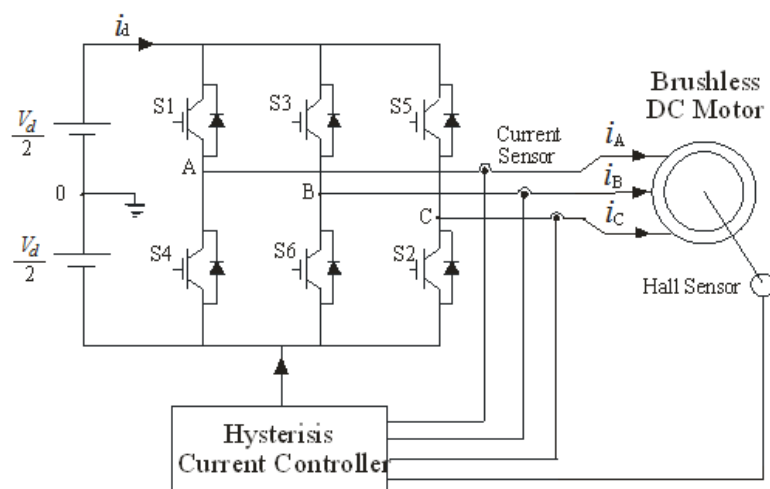


Figure 1: BLDC Motor Drive Block

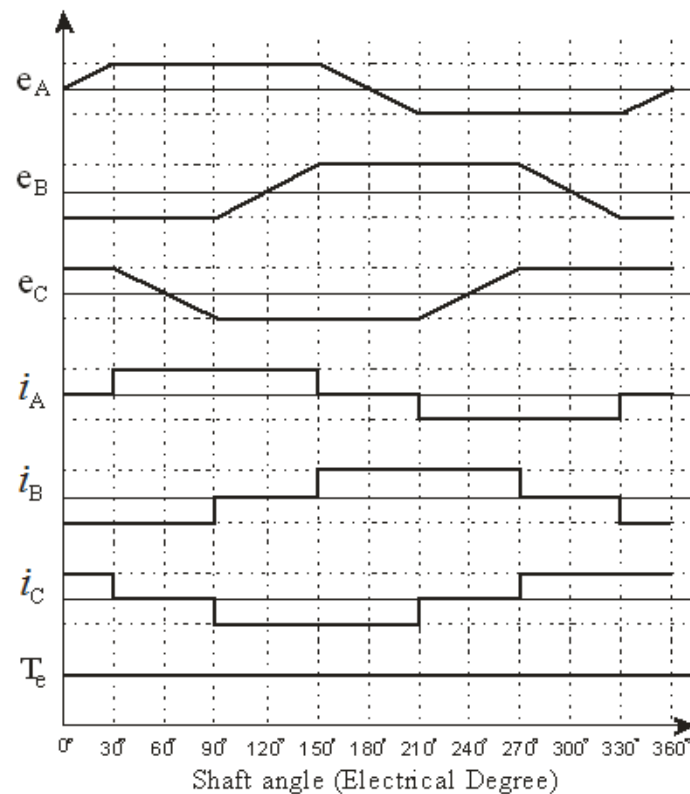


Figure 2: Waveforms of Back EMF and Phase Currents

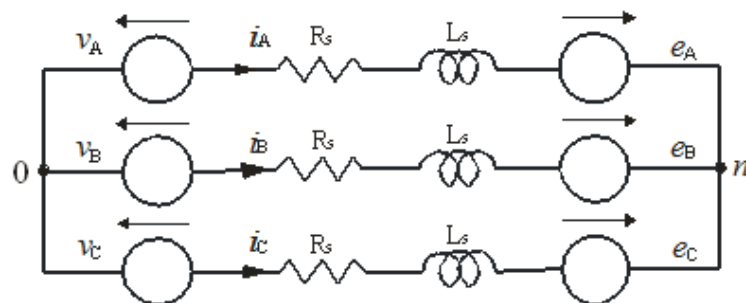


Figure 3: Equivalent Circuit Diagram of BLDC Motor

Assumptions are made that the BLDC motor is three phase symmetrical, star connected, neglect eddy current losses and hysteresis losses, BLDC motor produces a trapezoidal back-EMF such as Figure 2, and therefore the excited current waveform is preferably rectangular-shaped. The phase resistances of the stator windings are assumed to be equal. Irrespective of rotor position, the self and mutual inductances are constant due to surface mounted permanent magnet rotor topology. The damper windings are absent and the rotor-induced currents are neglected.

Its equivalent circuit is shown in figure 3. R , L are the resistance and inductance of the stator windings respectively; e_A , e_B , e_C are the counter emfs of the corresponding phase windings respectively; i_A , i_B , i_C are the corresponding phase currents respectively. The stator phase currents are considered to be balanced, i.e.,

$$i_A + i_B + i_C = 0 \quad (1)$$

The simplified matrix model of the BLDC motor is

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} L_s & 0 & 0 \\ 0 & L_s & 0 \\ 0 & 0 & L_s \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} e_A \\ e_B \\ e_C \end{bmatrix}$$

The counter emf of every phase winding is a trapezoidal wave form with a flat-top width greater than or equal to 120° electrical degree, and its flat-top amplitude is E_m . When the motor works in three phase six-state 120° turn-on mode, the current don't commutates instantaneously as a result of the inductance of the armature winding. For example, Take the power switch S_1 and S_2 's turn on to S_2 and S_3 's turn-on for example. During the commutation, it is gained as follows

$$e_A = e_B = e_C = E_m \quad (2)$$

suppose that the mechanical angular velocity of the rotor is ω , the torque can be obtained as follows during the commutation process.

$$T_e = \frac{e_A i_A + e_B i_B + e_C i_C}{\omega} = \frac{2E_m i_C}{\omega} \quad (3)$$

It is obvious from(3) that the torque is proportional to the non-commutative phase current during commutation, i.e. the commutation torque ripple can be eliminated so long as non-commutation phase current remains constant during commutation.

Commutation Process without Considering Effect of Hysteresis Current Control

It is assumed that the circuit status changes from phase A and phase C's turn-on to phase B and phase C's turn-on, phase A current flows D_4 and decays to zero gradually, while phase B current gradually increases to the maximum and reaches its steady-state value. The circuit equation during commutation can be written as follows.

$$L \frac{di_A}{dt} + r i_A + e_A - \left(L \frac{di_C}{dt} + r i_C + e_C \right) = 0 \quad (4)$$

$$L \frac{di_B}{dt} + r i_B + e_B - \left(L \frac{di_C}{dt} + r i_C + e_C \right) = U_d$$

Compared with the winding time constant L/R of a BLDC motor, then $|r i_x| \ll \left| L \frac{di_x}{dt} \right|$ ($x=A,B,C$) So the effect of the armature winding resistance can be neglected. Moreover the initial and final values of every phase current equal every phase steady-state current value I_0 before and after the commutation. All phase currents during the commutation can be obtained from (1), (2) and (4)

$$\begin{aligned} i_A &= I_0 - \frac{U_d + 2E_m}{3L} t \\ i_B &= \frac{2(U_d - E_m)}{3L} t \\ i_C &= -I_0 - \frac{U_d - 4E_m}{3L} t \end{aligned} \quad (5)$$

Then the torque during the commutation can be written

$$T_e = \frac{2E_m}{\omega} \left(I_0 + \frac{U_d - 4E_m}{3L} t \right) \quad (6)$$

From(5), the turn-off time t_{off} of phase A and the turn-on time t_{on} of phase B during the commutation process are

$$t_{off} = \frac{3LI_0}{U_d + 2E_m} \quad (7)$$

$$t_{on} = \frac{3LI_0}{2(U_d - E_m)} \quad (8)$$

From (5)~(8), the commutation between two phases can't be completed in the same time as $U_d > 4E_m$, i.e. the motor speed is less than a certain value, and as a result i_B has reached its steady-state value before i_A falls to 0, shown in figure 4.(I). What's more, the commutation leads to an increase in the amplitude of torque. The torque ripple can be obtained

$$T_r = \frac{E_m I_0}{\omega} * \frac{U_d - 4E_m}{U_d - E_m} \quad (9)$$

The commutation between two phases can be completed in the same time as $U_d = 4E_m$, i.e. the motor runs at certain speed, and as result i_B has exactly reached its steady-state value when i_A falls to 0, shown in figure 4.(II). In this case, the torque remains constant during the commutation and its value equal the torque during the non-commutation process.

$$T_s = \frac{2E_m I_0}{\omega} \quad (10)$$

As $U_d < 4E_m$, i.e. the motor speed is greater than a certain value, the commutation between two phases can't be completed in the same time, and as result i_B doesn't reached its steady-state value when i_A falls to 0, shown in figure 4. (III). The commutation leads to a decrease in the amplitude of torque. The torque ripple can be obtained

$$T_r = \frac{2E_m I_0}{\omega} * \frac{U_d - 4E_m}{U_d + 2E_m} \quad (11)$$

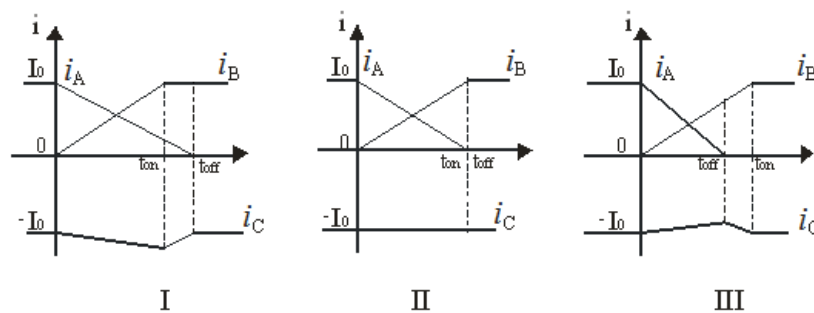


Figure 4: Waveforms of Phase Currents during Commutation in Different Cases

PRINCIPLE OF OPERATION OF HYSTERESIS CURRENT CONTROLLER

Among the various PWM techniques, the reliable and easy to implement is, hysteresis band current control. In addition to this, it also has very fast response current loop. The method does not need any knowledge of load parameters.

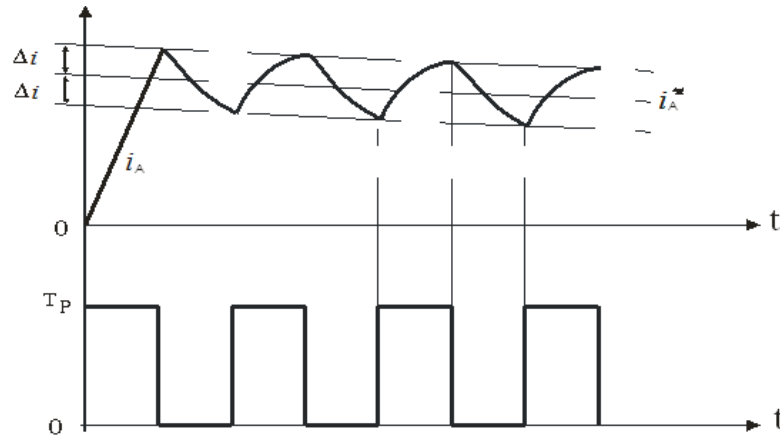


Figure 5: Hysteresis Controller Output Waveform

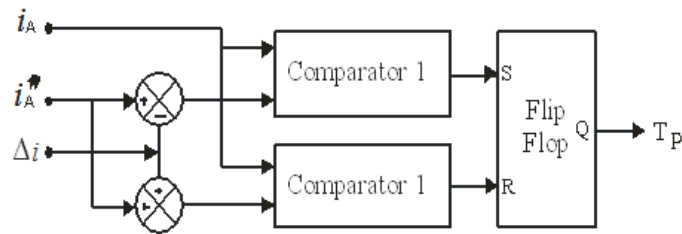


Figure 6: Block Diagram of Hysteresis Controller

The current can exceed the maximum limit, in between two consecutive switchings; if the PWM controller is sampled and held once a switching cycle, then the current is controlled on an average rather than on an instantaneous basis. In the hysteresis controller the current is controlled within a narrow band of excursion from its desired value. The hysteresis window determines the allowable or preset deviation of current, Δi . commanded current and actual current are shown in figure 5. with the hysteresis windows. The voltage applied to the load is determined by the following logic:

$$i_a \leq i_a^* - \Delta i, \text{ set } v_a = v_s$$

$$i_a \geq i_a^* + \Delta i, \text{ reset } v_a = 0$$

The realization of this logic is shown in figure 6. The window, Δi , can either be externally set as a constant or be made a fraction of armature current, by proper programming. The chopping frequency is a varying quantity, unlike the constant frequency in the PWM controller. This has the disadvantage of higher switching losses in the devices with increased switching frequency.

The T_p pulses issued from the hysteresis controller replace the block consisting of the comparator output in the figure 5. All other feature remains the same for the implementation of the hysteresis controller. This controller provides the fastest response, by means of its instantaneous action.

PROPOSED TORQUE CONTROL METHOD

This paper describes the Hysteresis Current Controller (HCC) method of minimization of torque ripple. This method depicts that instantaneous currents are sensed by using current sensors. The maximum torque is produced by every

60° commutation in switching circuits. All the three phases are conducted simultaneously due to the inductance of the armature. Let's assume the current switchover from phase A to B for a single commutation process. This switching is performed by turning off S1 and turning on S3. The phase current i_b increases through turn-on of S3 is called as incoming current. The phase current i_a decreases through turn-off of S1 is called as outgoing current. The outgoing current slowly decreases through the freewheeling diode D1. The current i_c remains unchanged during commutation called as un-commutated phase current.

The hysteresis current controller calculates the reference current by inverting the incoming phase current. Band width is set above and below the reference current. Maximum and minimum value of the instantaneous outgoing current is within the bandwidth. The fastest current control is possible if the bandwidth is small. HCC gives control pulses to the switches to extend the commutation period up to the incoming current reaches 80% of its instantaneous maximum value and then simply turn-off.

SIMULATION RESULTS

The simulation for permanent magnet brushless DC motor is done for 3 sec under different conditions- conventional control method with hysteresis control during commutation period. Figure 7 shows the waveform of phase current in conventional control method. During commutation period spicks are present in un-commutated phase current. Due to this torque ripple is present. Figure 8 shows the torque rippled waveform. Figure 9 shows the waveform of phase current in HCC control method. During commutation period current spicks are minimized by using HCC. Due to this torque ripple is apparently reduced compared with conventional control. Figure 10 shows the minimized torque rippled waveform. Figure 11 Shows the simulink model of proposed controller.

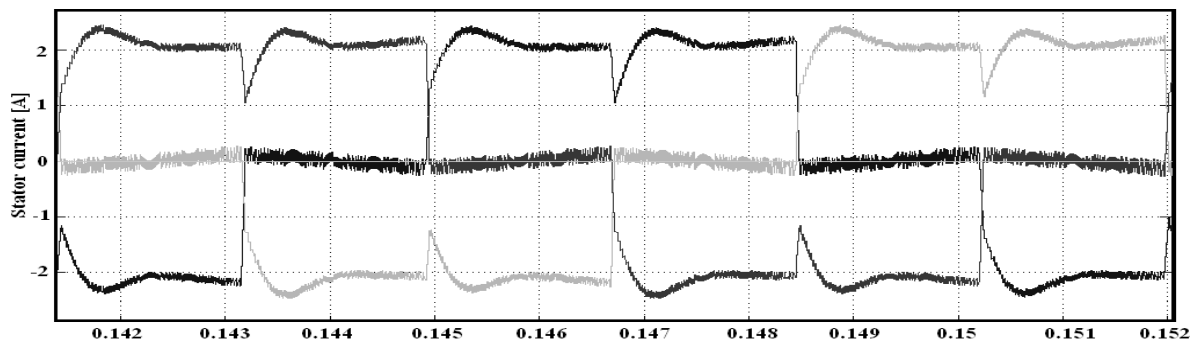


Figure 7: Waveforms of Phase Current without HCC

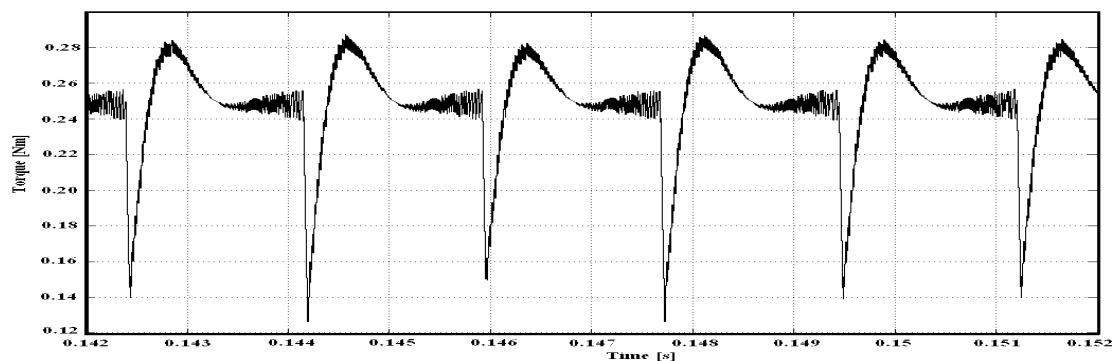


Figure 8: Waveforms of Torque Ripple Without HCC

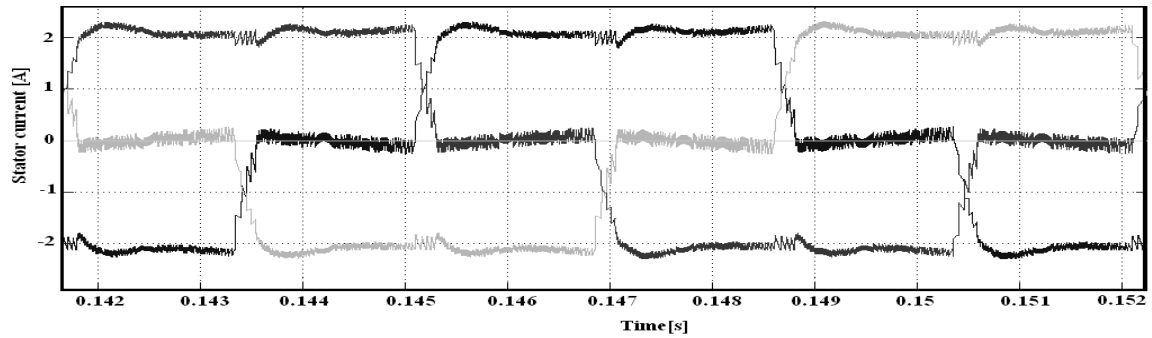


Figure 9: Waveforms of Phase Current with HCC

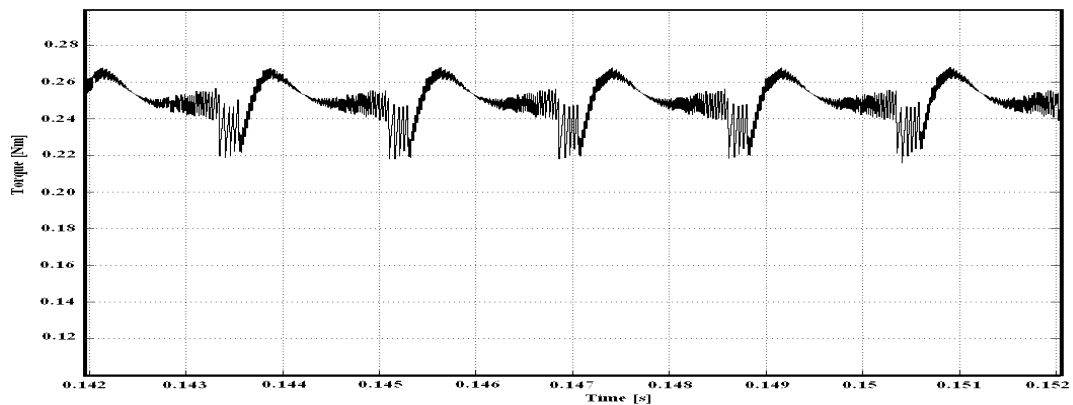


Figure 10: Waveforms of Torque Ripple with HCC

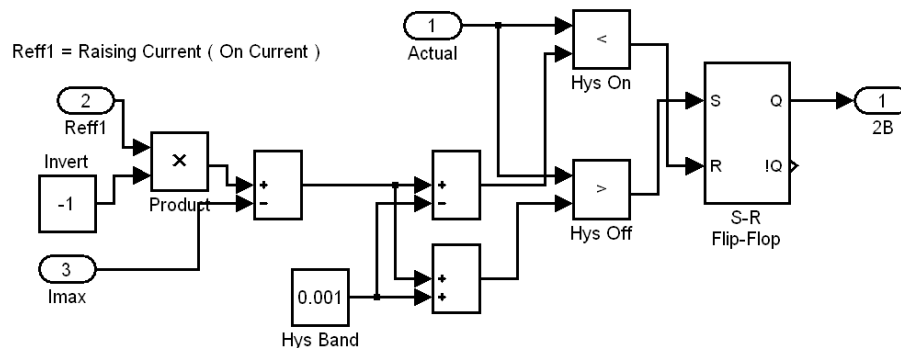


Figure 11: Simulink Model of Hysteresis Controller

MOTOR PARAMETERS

Voltage	24V
Power	50W
Phase Resistance	1.41 Ohm
Phase Inductance	0.25 mH
Torque constant	0.12 Nm/A

CONCLUSIONS

Thus with the hysteresis control method the torque ripple output of the PMBLDC motor is reduced in

commutation period as compared with the conventional control. This method is suitable for higher rating machines with any speed level and loads. It is also simple avoiding complexity in measuring various parameters of the motor.

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